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Investigation of the dependency of wind turbine loads on the simulation time

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Abstract

In this work the dependency of several wind turbine parameters with respect to the length of simulations used for their evaluation is investigated. The analysis is performed by computing the parameters with a different number of turbulent wind simulations, therefore simulation time, and repeating the computation with different turbulence realizations. The repetition of the computation is performed to identify the scatter of the parameters for a given number of turbulent seeds due to the different turbulence realization. The dependency on the simulation time of load variations due to changes in the collective pitch controller tuning is also investigated. Results show a significantly high dependency of the parameters and their variations on the turbulent wind realization. This dependency makes the use of turbulent wind simulation results not reliable for numerical optimization purposes.

1 Introduction

To improve the design of wind turbines holistic numerical optimization has become a useful tool [1–3]. An optimization procedure allows taking into account different design variables and constraints in an automated process, avoiding more time consuming manual iterations. An important problem related with numerical optimization is the selection of a cost function. The cost function should be representative of the model physics and should capture the effects of design variables changes on the system. Depending on the objective of the design the cost function can be different and its formulation can vary from very simple to complex. When wind turbine design is performed, several parameters have to be investigated to evaluate the goodness of the solution, e.g. annual energy production, maximum loads and fatigue loads. If several parameters need to be evaluated and to be included in the cost function, the selection of the cost model can become non-trivial and complex. When a detailed cost model is missing or the optimization is based on a model without enough detail to give the required informations, the cost of energy can be converted into changes of loads and performances computed during simulations. Using this approach the parameters have to be linked together, e.g. with constant weights, to obtain a scalar cost function. Alternatively a multi-objective Pareto front optimization can be performed. When the cost model is a function of parameters computed from a set of simulations, the design obtained is restricted to the specific case analyzed. Hence, it is required to investigate if the solution obtained is also valid for life time conditions. To improve the reliability of this approach it is necessary to understand how the loads computed in simulations and used in the cost function are representative of the wind turbine life time loads and within which limits the designer can rely on the obtained results. To obtain a reliable design a sufficiently large set of wind conditions must be taken into account to consider all the possible scenarios. When turbulent wind simulations are used to compute the loads, parameters might require different simulation time before settling to a value. Hence a cost function, based on these parameters, might be more or less sensitive to the number of turbulent wind conditions included in the computation. If the turbulent wind time series are fixed during the optimization procedure and they are not generated for every cost function evaluation the stochastic effect of the wind is reduced. Using the same wind boxes fixes a specific wind condition, but any change in the design would lead to a different wind turbine response and therefore to a different wind seen by the structure.

In this work we want to investigate the dependency of several wind turbine parameters with respect to the length of the turbulent wind simulations used for their evaluation. The increase in simulation time is obtained increasing the number of turbulent seeds used for the load evaluation. The dependency of the parameters is also investigated looking at their variation with respect to changes in the collective pitch proportional integral (PI) controller tuning.

This paper is divided as follows. First the methods used for the analysis are explained. In a following section the results of the parameters dependency and the parameters variations dependency on the simulation time are shown. The paper ends with some considerations and conclusions.

2 Method

All the analysis showed in this work is based on sets of multibody aeroservoelastic simulations performed with the code HAWC2 [4]. The simulations are performed for normal turbulent conditions with a turbulence intensity selected according to the standard [5] for a class B. The wind turbine selected for the investigation is the NREL reference 5 MW wind turbine [6]. The controller used to regulate the wind turbine is described in [7].

2.1 Dependency of parameters

The parameters analyzed in this investigation are the damage equivalent load (DEL), the standard deviation (STD), the mean value (MN), and the maximum value (MAX). These parameters are evaluated in different location of the wind turbine in order to have a description of the different components. The loads are the bending moments at the blade root (flapwise, edgewise and resultant), at the tower base (longitudinal, lateral and resultant), and at the end of the shaft on the generator side (torsional). All the loads, except the ones depending on maximum values, depend on the mean wind speed. Hence, to obtain a single parameter, they are weighted with a Weibull probability function to obtain the lifetime expected value.

A set of 2100 simulations is initially generated (100 turbulent seeds for 21 mean wind speeds each) for normal operation of power production. The simulations are then combined and post processed to obtain the parameters analyzed. The simulations that are post-processed together to lead to a single parameter are divided in sets with increasing number of turbulent seeds. The number of turbulent seeds goes from 1 to 20. Each set with a fixed number of turbulent seed is repeated 5 times, changing the wind speed realization. This division leads to 100 different simulation sets. For each of the 100 sets, 21 mean wind speeds, from 5 m/s to 25 m/s, are used for each turbulent seeds. Hence, the five sets that are composed by one turbulent seed include 21 simulations, while the five sets with 20 turbulent seeds are composed of 420 simulations (21 mean wind speeds times 20 different turbulent seeds). Figure 1 shows a visualization of how the simulations are combined into the sets. In the graph the 100 sets are shown on the coordinate axis, while on the ordinate axis all the simulations at one mean wind speed are represented. Each of the 100 sets is post processed independently to compute the performances and the parameters at the different wind turbine locations.

All the parameters shown in the investigation are normalized with respect to the same parameter computed with 21 mean wind speeds and 100 turbulent seeds

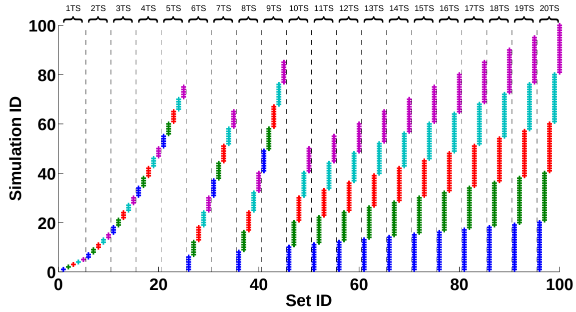


Figure 1: Visualization of sets used for the postprocessing.

2.2 Dependency of parameter variations

The parameters analyzed in this investigations are the damage equivalent load (DEL) and the standard deviation (STD) of the blade root flapwise bending moment and of the tower base longitudinal bending moment. Also the standard deviation of the rotational speed is investigated.

The analysis of parameter variations is performed only at the wind speed of 15 m/s. Two sets of simulations are generated.The two sets are formed by 100 simulations with 100 different turbulence realizations. The two sets differs on the type of gain scheduling used [8]. A linear gain scheduling is used for the first controller setting while a quadratic, that includes both aerodynamic gain and aerodynamic damping, is used for the second. The different gain-scheduling schemes lead to a difference in the regulator mode frequency and damping. One controller has a lower regulator mode frequency. The difference in the regulator mode frequency is about 12 %. Since one controller has lower frequency, this controller leads to a less aggressive regulation, hence higher rotational speed variations and lower tower base bending moments. Two analysis of these sets are performed. First the variation of the parameters is evaluated using only one wind realization for both the controller settings. This investigation shows how the loads are sensitive to the wind turbulence even when using the same wind realization. Secondly the variation is evaluated while increasing the number of turbulence seeds used for the evaluation of the parameters. With this analysis it is expected to evaluate how many turbulence seeds are required in order to get a parameter variation that is consistent and independent of the set of simulations considered.

3 Results

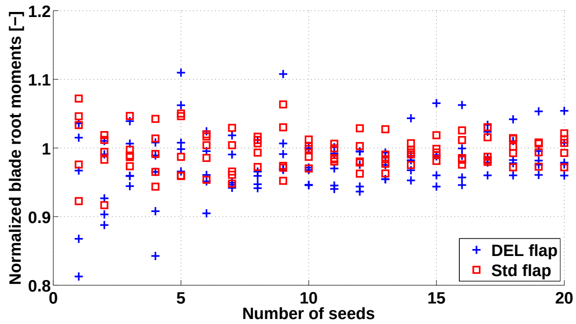
3.1 Dependency of parameters

In this section the dependency of the parameters is analyzed with respect to the increasing number of turbulent seeds used for their evaluation.

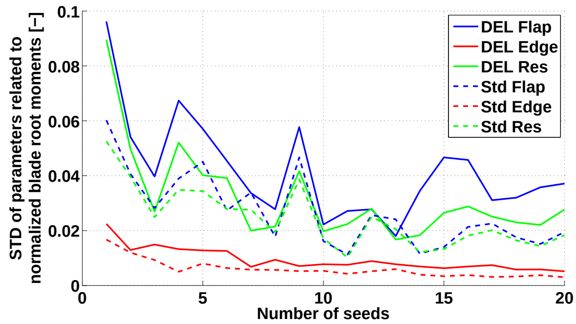
Figure 2 shows the mean power and the DEL of the blade root flapwise bending moment computed from all the simulations. It appears clearly how the parameters at the same mean wind speed are scattered due to the different turbulence seeds. Each turbulent box leads to a different load value and the scatter at the same mean wind speed can be significant.

Figure 3 shows how blade root DELs and STD change when increasing the number of turbulent seeds. The standard deviation of the 5 samples for each number of turbulent seed is shown in Figure 3 b. The scatter of the samples decreases faster within the first five seeds. The standard deviation of the parameters in the edgewise component after five seeds is not significantly reduced. In the flapwise direction a reduction of the scatter is still present after ten seeds but at a non monotonic and slower rate. The DELs seem to have lower scatter compared to the STD.

Figure 4 shows how the MAX load and the MN load at the tower base are affected by the number of turbulence seeds. As expected the MAX value, since it is a non linear function and does not depend on integrals, shows a large spread of the samples for the three loads. This scatter in the data shows clearly

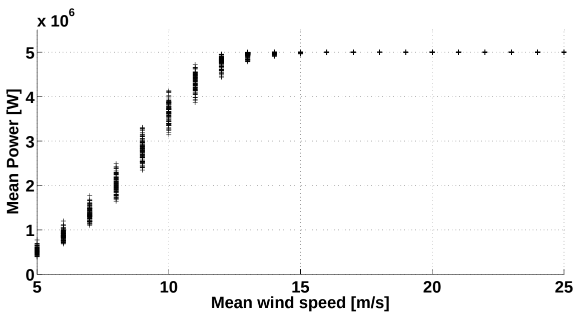


a) Samples.

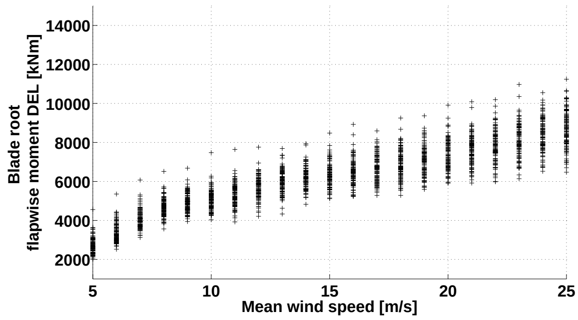


b) Standard deviation.

Figure 3: Dependency of blade DELs and standard deviations on the number of turbulent seeds. Samples and their standard deviations.

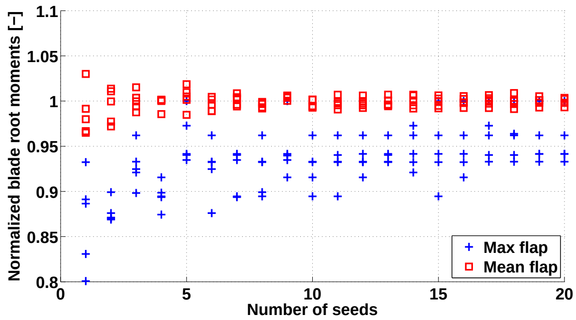


a) Mean power.

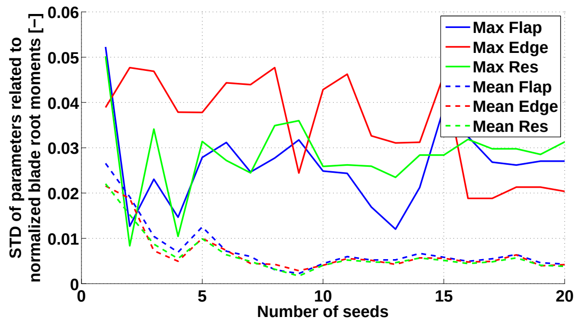


b) Blade root flapwise moment DEL.

Figure 2: Example of scatter of loads computed for 100 different turbulent seeds for each mean wind speed.



a) Samples.



b) Standard deviation.

Figure 4: Dependency of blade DELs and standard deviations on the number of turbulent seeds. Samples and their standard deviations.

that to identify the maximum value of a load, with a good fidelity level, a very large number of simulations is needed. The MN value samples have a lower standard deviation. The scatter of the MN value samples does not change significantly after ten turbulent seeds.

Figure 5 shows the dependency of the resultant of the bending moments at the tower base. The standard deviation, Figure 5 b, of all parameters but the maximum value decreases for an increasing number of turbulent seeds. The scatter of the DEL is lower than the one of the STD for most of the cases, but the STD seem to decrease constantly while the DEL, after five turbulent seeds, seems not to reduce the scatter any longer.

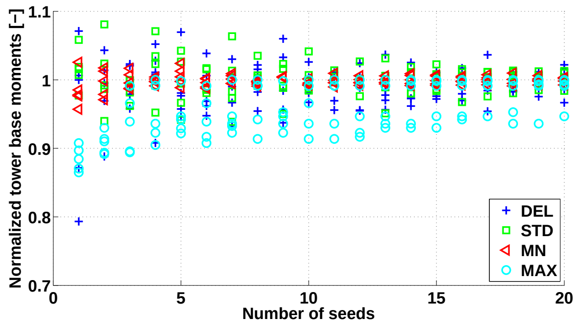
Figure 6 shows the dependency of the shaft torque. The accuracy of the DEL samples appear to be higher on the shaft compared to the other components. Already with five turbulent seeds the standard deviation is lower than 1%. Also in this case the standard deviation of the STD decreases more slowly and less smoothly compared to the DEL. Also in this case it is necessary to include many simulations in the computation of the loads to capture the maximum value.

These results show the sensitivity of wind turbine parameters on the length of the simulation used to evaluate them. Even with a very high number of turbulent seeds the dependency can be considerably high.

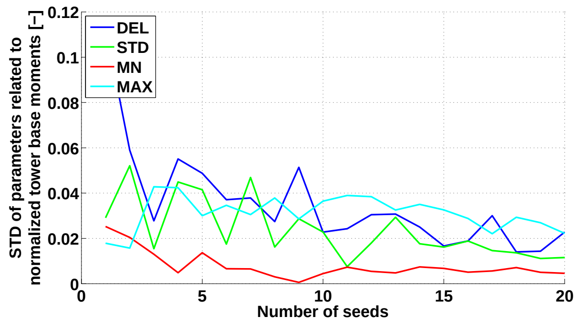
3.2 Dependency of parameters variation

In this section the dependency of the variation of wind turbines parameters is evaluated. First the variations are compared using one seed at the time and looking at their dependency on the wind realization. After the dependency on the number of turbulent seeds is evaluated.

Figure 7 shows the variation of the blade root flapwise bending moment DEL and STD (a), of the tower base longitudinal bending moment DEL and STD (b), and of the rotor rotational speed standard deviation (c). The loads variations are shown for each of the 100 turbulent seed at a wind speed of 15 m/s. From the figure it appears that a large scatter of the variations is present. The different turbulent wind leads to load variations that differs significantly from each other. For both blade and tower loads and both DEL and STD, positive and negative values are present. The blade loads variations range between $\pm 11\,\%$ while tower loads between $-14\,\%$ and $5\,\%$. This behavior means that when changing a parameter the evaluation of its effect on the loads can be hidden and dominated by the wind realization. For the tower load an overall reduction can be noticed but the scatter has the same range as the mean value of the

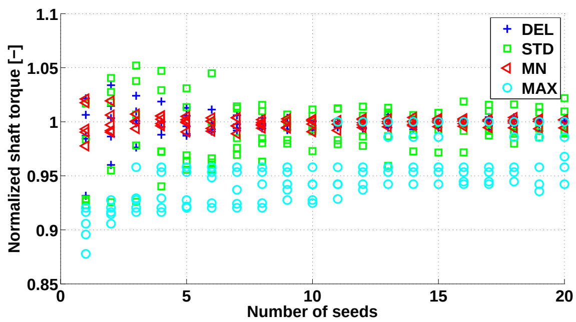


a) Samples.

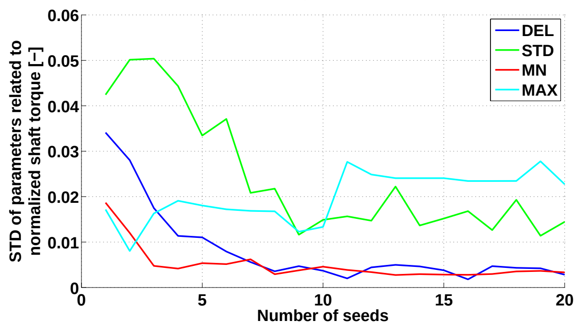


b) Standard deviation.

Figure 5: Dependency of tower DELs, standard deviations, mean and maximum values on the number of turbulent seeds. Samples and their standard deviations.

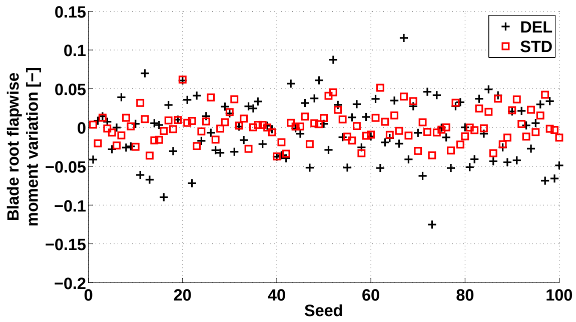


a) Samples.

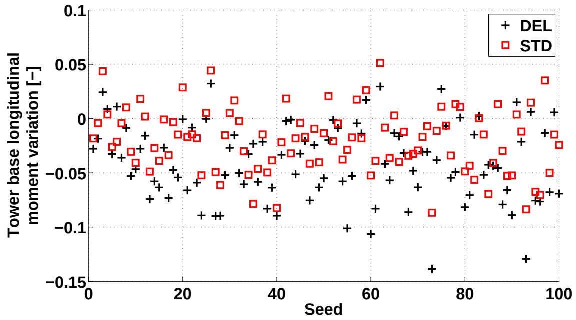


b) Standard deviation.

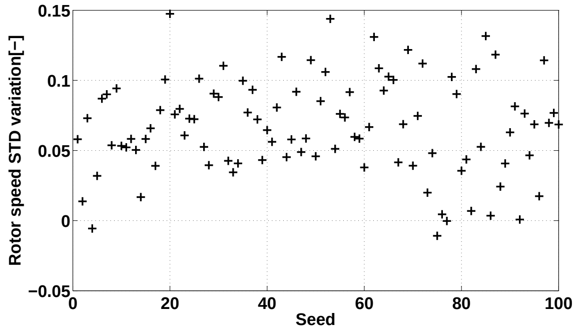
Figure 6: Dependency of shaft torque DELs, standard deviations, mean and maximum values on the number of turbulent seeds. Samples and their standard deviations.



a) Blade root flapwise bending moment.



b) Tower base longitudinal bending moment.

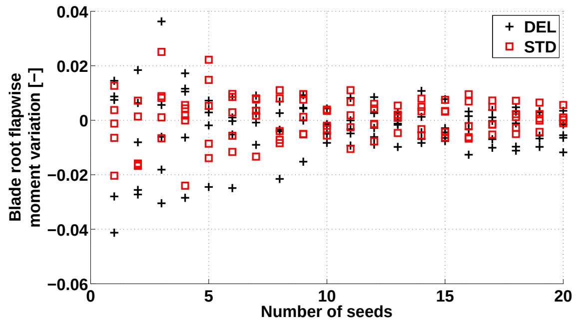


c) Rotor speed standard deviations.

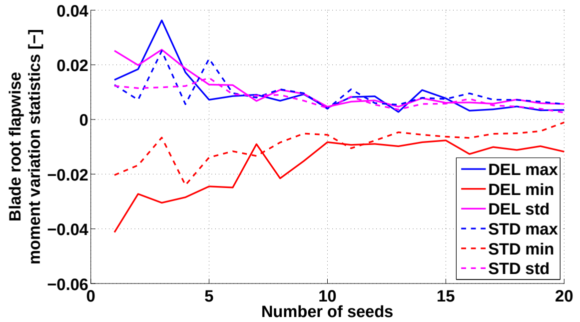
Figure 7: Dependency of DELs and standard deviations variations on the turbulent seed. Wind speed of 15 m/s.

samples. The rotor speed standard deviation variation appears to be mostly increasing, only few wind realization lead to a negative value. An estimation of the effect of one wind turbine parameter on the rotor speed standard deviation is completely dominated by the turbulent wind effects. These results show that when evaluating loads variations with only one turbulent seed the results obtained are dominated by the turbulent wind load variations effects.

Figure 8 shows the dependency of blade root flapwise bending moment DEL and STD variations on the number of turbulence seeds used for their evaluation. The figure shows both values and statistics of the variations. Increasing the number of turbulent seeds a reduction in the scatter of the variations appears. The range of the samples decreases but non monotonically. The blade flapwise moment standard deviation variation scatter is lower compared to the



a) Values.



b) Statistics.

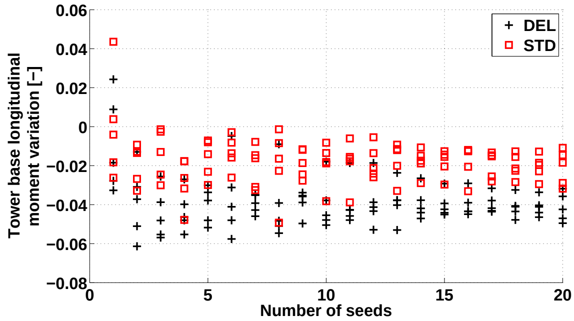
Figure 8: Dependency of blade root flapwise bending moment DELs and standard deviations variations on the number of turbulent seed. Wind speed of 15 m/s.

one associated with the DEL, especially when using few turbulent seeds. Even with 20 turbulent seeds the scatter appears to be too large for numerical applications where a numerical gradient evaluation is required.

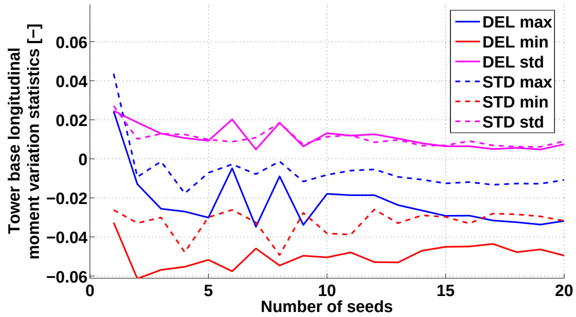
In Figure 9 the dependency of the tower base longitudinal bending moment DEL and STD is shown. Also in this case the values and the statistics are shown. At the tower base the variation becomes always negative when using 2 or more turbulent seeds. Despite the consistency in the load reduction the variations ranges of 2 % even when using 20 turbulent seeds. The scatter of the values is of the same amplitude as the mean value of the variations, especially for the standard deviation.

Figure 10 shows the dependency of the rotor speed standard deviation variation on the number of turbulent seeds. Values and statistics are shown. The rotational speed standard deviation variation has a scatter of almost 2 % even when using 20 turbulent seeds. These variations are always consistently positive if using more than one turbulent seed. Again the variations do not converge monotonically towards a value but oscillations are presents when increasing the length of the simulation.

From this analysis it appears that the variation of the parameter analyzed due to a change in the controller settings is differently affected by the turbulent wind realization. If the parameter is not very sensitive to the controller settings a scatter around zero

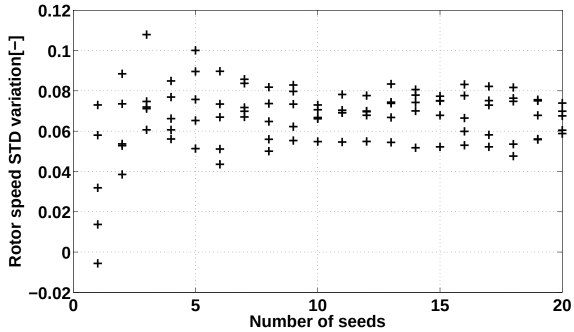


a) Values.

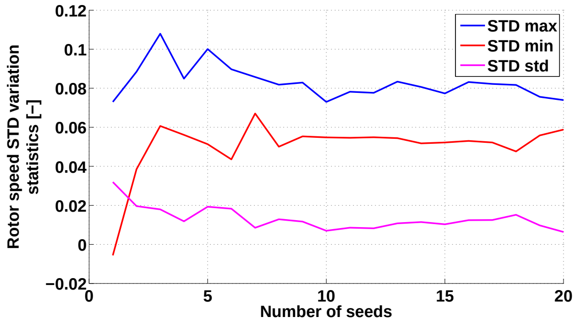


b) Statistics.

Figure 9: Dependency of tower base longitudinal bending momen DELs and standard deviations variations on the number of turbulent seed. Wind speed of 15 m/s.



a) Values.



b) Statistics.

Figure 10: Dependency of rotor speed standard deviations variations on the number of turbulent seed. Wind speed of 15 m/s.

is present due to the wind. In numerical optimization this variation would be interpreted as a setting dependency and therefore it would mislead the optimization algorithm. If the parameter is more sensitive to the settings then it is always possible to obtain a consistent direction of variation but many turbulent seeds might be needed. In this case a misinterpretation of the actual value of the gradient would be anyway present even with many wind realizations.

4 Conclusions

From this investigations it appears that even with a high number of turbulent wind simulations, wind turbines loads depend on the turbulence realization that is used for their evaluation. When variations in the loads due to changes in parameters are evaluated the effect of the parameter itself can be comparable with the changes due to the different wind seen by the wind turbine. This behavior can be problematic when performing numerical optimization. Changes in the loads due to the wind seen by the wind turbine can be attributed to changes in the design variables. This attribution would lead to a wrong estimation of the dependency of the cost function from the design parameters. Hence the optimization would not converge or it would but not to a significant minimum point for the design. Caution must be taken when evaluating loads and parameters from turbulent wind aeroelastic simulations.

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